Progress in jet reconstruction and heavy ion collisions

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DOI: will be assigned

We review recent developements related to jet clustering algorithms and jet reconstruction, with particular emphasis on their implications in heavy ion collisions. These developements include fast implementations of sequential recombination algorithms, new IRC safe algorithms, quantitative determination of jet areas and quality measures for jet finding, among many others. We also show how jet reconstruction provides a useful tool to probe the characteristics of the hot and dense medium created in heavy ion collisions, which allows one to distinguish between different models of parton-medium interaction.

Recent developements in jet algorithms With the upcoming start-up of the proton-proton and heavy ion programs at the LHC, jet reconstruction techniques have been the subject of intense research in the recent years [1–4]. In this contribution we briefly review this progress with special emphasis on their implications in heavy ion collisions.

An important developement has been the fast implementation of the k_T [5] and Cambridge/Aachen [6, 7] jet algorithms. Prior to 2005, existing implementations scaled as N^3, with N the number of particles to be clustered, thus making it unpractical for high multiplicity proton-proton collisions, and even more in heavy ion collisions (HIC). Thanks to computational geometry methods, the performance of these algorithms was made to scale as $N \ln N$ [8]. These fast implementations are available through the `FastJet` package [9], together with area-based subtraction methods and plugins to external jet finders.

Another important achievement has been the formulation of a practical (scaling as $N^2 \ln N$) infrared and collinear (IRC) safe cone algorithm, SISCone [10]. Unlike all other commonly used cone algorithms, SISCone is IRC safe to all orders in perturbation theory by construction. This property allows one to compare any perturbative computation with experimental data, which for IRC unsafe algorithms is impossible beyond some fixed order [10]. The phenomenological implications of SISCone when compared with the (IRC unsafe) commonly used MidPoint cone algorithm range from few percent differences in the inclusive jet spectrum, somewhat larger in the presence of realistic Underlying Event (UE), up to 50% differences for more exclusive observables, like jet-mass spectra in multi-jet events.

Another recently developed IRC safe jet algorithm is the anti-k_t algorithm [11]. This algorithm is related to k_T and Cam/Aa by its distance measure, $d_{ij} \equiv \min(k_{ti}^{2p}, k_{tj}^{2p})\Delta R_{ij}^2/R^2$, with $p = -1$ ($p = 1$ corresponds to k_T and $p = 0$ to Cam/Aa). The anti-k_T algorithm has the property of being soft-resilient, that is, due to its distance soft particles are always clustered with hard particles first. This property leads to rather regular jet areas, which become perfectly circular in the limit in which all hard particles are separated in the (y, ϕ) plane by at least a

distance $2R$ [11]. Another important advantage of the anti-k_t algorithm is that it has a very small back-reaction, that is, the presence of a soft background has reduced effects on which hard particles are clustered into a given jet. This is a particularly relevant advantage of the anti-k_t algorithm for jet reconstruction in very dense environments like heavy ion collisions.

There has been historically some confusion about the concept of the *area* of a jet, specially since the naive expectation $A_{\rm jet} = \pi R^2$ only holds at leading order. The situation was recently clarified by the introduction of quantitative definitions of jet areas based on the *catchment* properties of hard jets with respect to very soft particles, called *ghosts* in [12]. On top of their theoretical interest, jet areas have important applications related to the subtraction of soft backgrounds coming from the UE or from Pile-Up (PU), both in proton-proton and in heavy-ion collisions, as discussed in [13].

Performance of jet algorithms A recurring question in jet studies is "what is the best jet definition for a given specific analysis under certain experimental conditions"? Most existing techniques either use as a reference unphysical Monte Carlo partons (an ambiguous concept beyond LO) and/or assume some shape for the measured kinematical distributions, typically a gaussian. To overcome these disadvantages, a new strategy to quantify the performance of jet definitions in kinematic reconstruction tasks has been recently introduced [14], which was designed to make use exclusively of physical observables. Related studies which address the same question were discussed in Ref. [15, 16].

In Ref. [14] two quality measures respecting the above requirements are proposed, and applied to the kinematic reconstruction of invariant mass distributions in dijet events from hadronically decaying heavy resonances in simulated LHC proton-proton collisions for a wide range of energies. These quality measures can in turn be mapped into an effective luminosity ratio, defined as

$$\rho_{\mathcal{L}}(\mathrm{JD}_2/\mathrm{JD}_1) \equiv \frac{\mathcal{L}(\text{needed with JD}_2)}{\mathcal{L}(\text{needed with JD}_1)} = \left[\frac{\Sigma\,(\mathrm{JD}_1)}{\Sigma\,(\mathrm{JD}_2)}\right]^2 . \tag{1}$$

Given a certain signal significance Σ with jet definition JD_2, $\rho_{\mathcal{L}}(\mathrm{JD}_2/\mathrm{JD}_1)$ indicates the factor more luminosity needed to obtain the same significance as with jet definition JD_1.

The results of [14] over a large range of jet definitions,[1] summarized in Fig.. 1, indicate that for gluon jets, and in general for TeV scales, there are significant benefits to be had from using larger radii that those commonly used, up to $R \gtrsim 1$, while smaller radii are favored for smaller values of the jet p_T. In general, SISCone and C/A-filt (Cam/Aa supplemented with a filtering procedure [18]) show the best performance. These conclusions are robust in the presence of high-luminosity PU, when subtracted with the jet area technique [13].

The same philosophy could be applied to heavy ion collisions to determine how in such case the optimal jet definition is affected by the overwhelming underlying event present. It is clear however that in this case the quality measures are different from the proton-proton case: for example, for HIC resonance reconstruction is not a relevant quality measure.

Jet reconstruction in heavy ion collisions While QCD jets are ubiquitous in pp collisions, until recently [19, 20] no real jet reconstruction had been obtained in the much more challenging environment of HIC. Indeed, usually in HIC one refers to a single hard particle in the event

[1] There results can also be accessed through an interactive web tool [17] which allows the user to compare the jet finding quality for a wide range of parameters (jet algorithm, R, value of PU, ...).

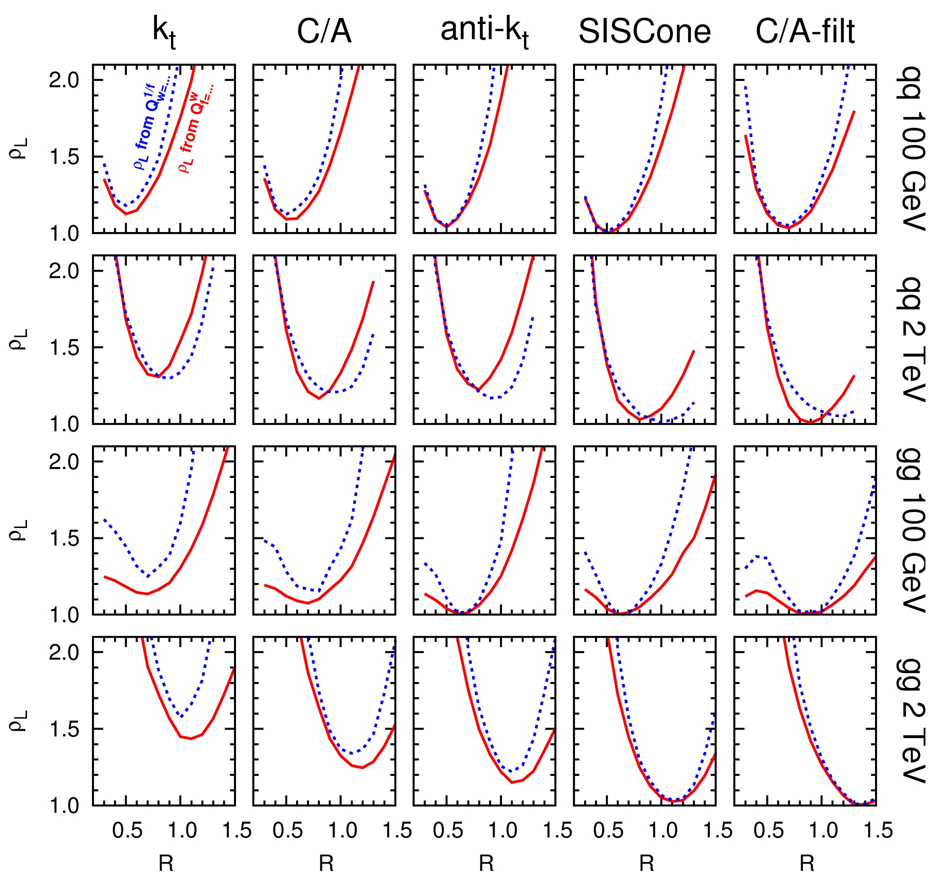

Figure 1: The effective luminosity ratio, Eq. 1, for quark and gluon jets at 100 GeV and 2 TeV, from Ref. [14].

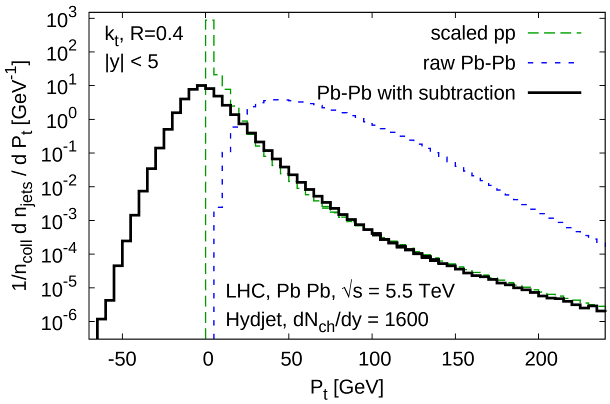

Figure 2: The simulated inclusive jet spectrum at the LHC with the k_T algorithm, including subtraction, from Ref. [13].

as a *jet*. However, reconstructing full QCD jets provides a much more precise window to the properties of the hot and dense medium created in the collision than just leading particles.

The difficulty in reconstructing jets in HIC stems from the huge backgrounds, which need to be subtracted in order to compare with baseline results, like proton-proton or proton-ion collisions at the same energy. There are various techniques to subtract such large backgrounds. In Ref. [13] it was shown how the area method introduced above could efficiently subtract large UE backgrounds in HIC for LHC conditions with good accuracy, see Fig. 2.

It is therefore important for precision measurements to control the accuracy of the subtraction procedure intrinsic to jet reconstruction in HIC, as well as to understand the differences between the performances of different jet algorithms. Ongoing studies [21] suggest that one of the dominant sources of systematic error in HIC jet reconstruction is back-reaction [12], therefore anti-k_t is potentially interesting in this situation due to its small back-reaction [11]. Ref. [21] also investigates the use of local ranges for the determination of the background level ρ as a technique to reduce the effects of point-to-point background fluctuations.

Related to progress in jet reconstruction algorithms, an important developement in recent years has been the developement of several exclusive Monte Carlo event generators for heavy ion collisions which account for the interaction of partons propagating within the hot and dense medium created in the collision [22–25]. These event generators, which assume different models for the parton-medium interaction [26], can be used together with modern jet reconstruction techniques in order to determine, under realistic experimental conditions, which jet-related observables are at the same time more robust and more sensitive to the different scenarios for the hot and dense medium dynamics.

As an illustration of how these Monte Carlo programs with medium effects can be coupled to jet reconstruction techniques and be used to determine medium properties in HIC, in Fig. 3 we show preliminary results for two observables which are sensitive to medium effects: the dijet azimuthal correlations and the jet shape. Jet shapes are defined analogously to [22]. To obtain these results, hard events with $p_T^{\rm min} = 100$ GeV are generated and then propagated through a model of the hot medium by means of the `Q-PYTHIA` Monte Carlo [22], for different values of the medium parameters. The resulting hadronic event is embedded into a minimum bias PbPb

event generated with the PSM Monte Carlo [27] for different scenarios of central multiplicity at the LHC. Jet reconstruction is performed with different algorithms of the `FastJet` package, and UE subtraction is performed with the jet area method. In the particular examples of Fig. 3 the C/A(filt) and anti-k_T algorithms are used with the jet radius chosen to be $R = 0.5$.

For the two examples of Fig. 3, we show the proton-proton baseline results with and without parton-medium interactions, whose strength is characterized by the parameter $\hat{q}L$ [22], with L the medium length. The medium effects are clearly visible for the two observables, inducing a broadening of the jet shape [28], and a decorrelation of the dijet azimuthal spectrum. These curves, with no HIC UE, are labelled as *'No PbPb'*. Note in the case of dijet correlations that dijet angles are typically better measured than p_T spectra, so this observable is a promising candidate for an early measurement at the LHC to characterize the hot medium.

Then we also show the corresponding results when the pp event is embedded into the PbPb event, in which case the UE event has been subtracted with the area method. These curves are labelled as *'PbPb, subtraction'*. We observe how after the background subtraction the baseline proton-proton results are reasonably recovered, in both cases with ($\hat{q}L \neq 0$) and without ($\hat{q}L = 0$) medium effects.

These preliminary results indicate that medium-sensitive jet related observables can be accurately reconstructed even in the presence of large backgrounds, and are thus useful probes of the details of the parton-medium interactions. More work however is required to quantify the accuracy with which the hot and dense medium created in HIC, and the values of the parameters which characterize it, can be studied by reconstructed jets and related observables.

Acknowledgments The author wants to acknowledge M. Cacciari, G. Salam and G. Soyez for collaboration in this research and for suggestions on this write-up, as well as N. Armesto and C. Salgado for assistance with `Q-PYTHIA`.

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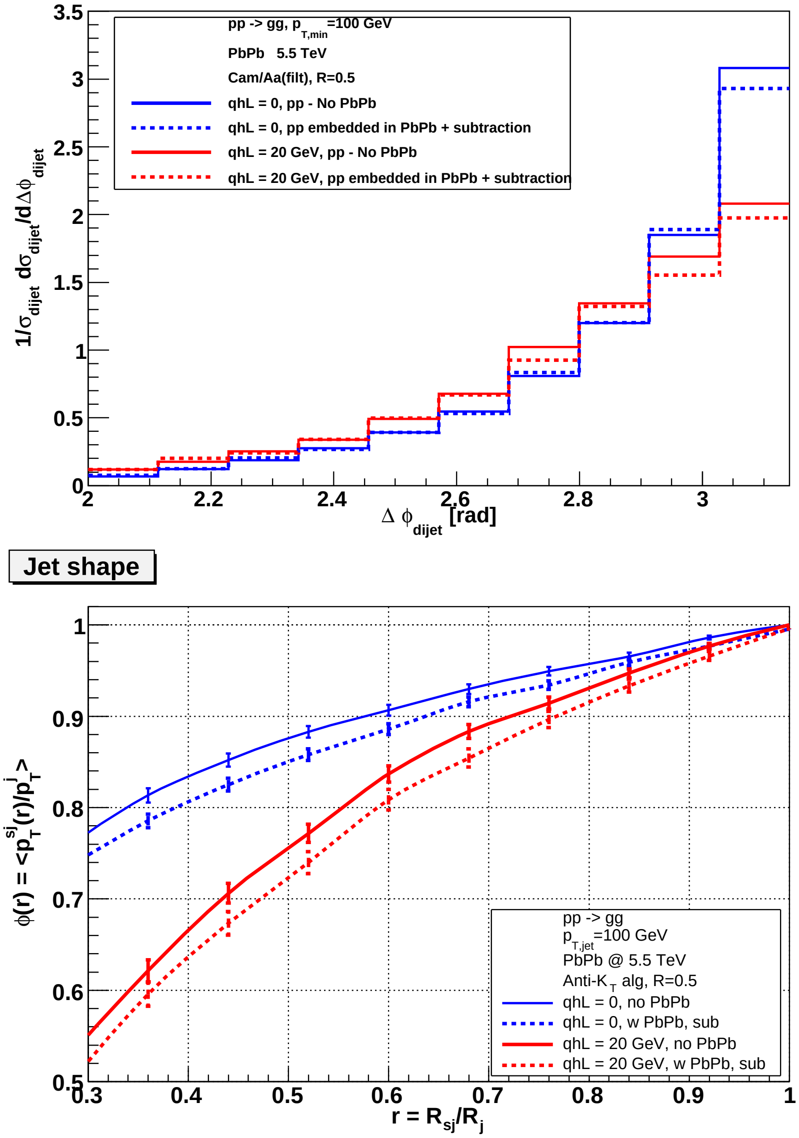

Figure 3: Preliminary results for full jet reconstruction, including background subtraction, of jet-related observables under realistic experimental conditions at the LHC: dijet azimuthal correlations (upper plot) and jet shapes (lower plot). See text for details.

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